ISSN 0145-8752, Moscow University Geology Bulletin, 2016, Vol. 71, No. 6, pp. 445–450. © Allerton Press, Inc., 2016.
Original Russian Text © K.Yu. Vasilieva, E.A. Bakay, V.B. Ershova, R.R. Khusnitdinov, A.K. Khudoley, E.V. Kozlova, S.A. Soloveva, 2016, published in Vestnik Moskovskogo Universiteta, Seriya 4: Geologiya, 2016, No. 5, pp. 76–80.

The Subsidence and Thermal History of the Baikit Anteclise Sedimentary Basin

K. Yu. Vasilieva[a], *, E. A. Bakay[b], **, V. B. Ershova[a], *, R. R. Khusnitdinov[c], ****, A. K. Khudoley[a], *****, E. V. Kozlova[d], ******, and S. A. Soloveva[c], *********

[a]St. Petersburg State University, St. Petersburg, Russia
[b]Moscow State University, Moscow, Russia
[c]Gazpromneft STC, Russia
[d]Skoltech, Russia
**e-mail: k.vasilyeva@spbu.ru*
***e-mail: bakay@geol.msu.ru*
****e-mail: v.ershova@spbu.ru*
*****e-mail: Khusnitdinov.RR@gazpromneft-ntc.ru*
******e-mail: a.khudoley@spbu.ru*
*******e-mail: miliyakozlova@mail.ru*
********e-mail: Soloveva.SA@gazpromneft-ntc.ru*
Received December 9, 2015

Abstract—The Riphean rocks of the Baikit anteclise have been examined using pyrolysis Rock–Eval 6 to evaluate the subsidence history and erosion level. The studied Riphean rocks have the MK_3–MK_4 catagenesis grade. Based on the catagenesis of organic matter we propose a model of maximum burial before the beginning of the accumulation of Vendian deposits. Estimated calculations of subsidence and erosion have shown that the assessed catagenesis grade could be reached at a depth of 7 km, while the erosion level was approximately 5–7 km.

Keywords: Riphean sediments, Baikit anteclise, Rock–Eval, thermal history of sedimentary basin
DOI: 10.3103/S0145875216060120

INTRODUCTION

The history of subsidence and uplift is an important problem for research of sedimentary basins (Allen and Allen, 2013). Subsidence and uplift control the beginning and proceeding of catagenesis phases, and oil generation, as well as the formation and destruction of hydrocarbon deposits. In particular, this task is difficult when studying ancient sedimentary rocks that underwent repeated post-sedimentation alterations. The authors have attempted to reconstruct the thermal history of part of the Baikit anteclise (the southwest Siberian platform) in the Kuyumba group of deposits (Fig. 1).

In the study area Archaean–Lower Proterozoic basement rocks are overlain by Riphean and Vendian–Paleozoic sediments (*Stratigrafiya*, 2005; Kharahinov and Shlenkin, 2011). A Riphean complex of a predominantly carbonate composition that is approximately 4 km as thick forms the lower structural level: its rocks are dissected by numerous cracks and fractures and folds (Khabarov, Varaksina, 2011). Folding and erosion occurred after the sedimentation of the Riphean rocks; rocks of different Riphean stratigraphic levels were exposed to the surface (Kontorovich et al., 1996). The upper structural level (Vendian–Paleozoic with thickness of 2.5–2.6 km) rests upon the Riphean rocks with an angular unconformity. The main hydrocarbon reserves explored within the Kuyumba deposit are concentrated within the fracture–cavernous reservoir at the top of the Riphean section. Fluid-resistant layers are known in the Vendian–Cambrian deposits, while deposits of the Vedreshev, Madra and Iremeken units are regarded as petroleogenetic (Filiptsov et al., 1999; Frolov et al, 2015).

The Riphean section of the Kuyumba deposit is composed mainly of carbonate and clay rocks in which determination of the catagenesis stage by conventional petrographic methods is difficult (Yapaskurt, 2008). There are several approaches to the evaluation of the depth of subsidence of sedimentary complexes, and thus the degree of their catagenetic transformation (Allen and Allen, 2013; Ammosov et al., 1980; Yudovich and Ketris, 2011). For organic-rich mudstone the main method for assessing catagenetic transformation is the pyroly-

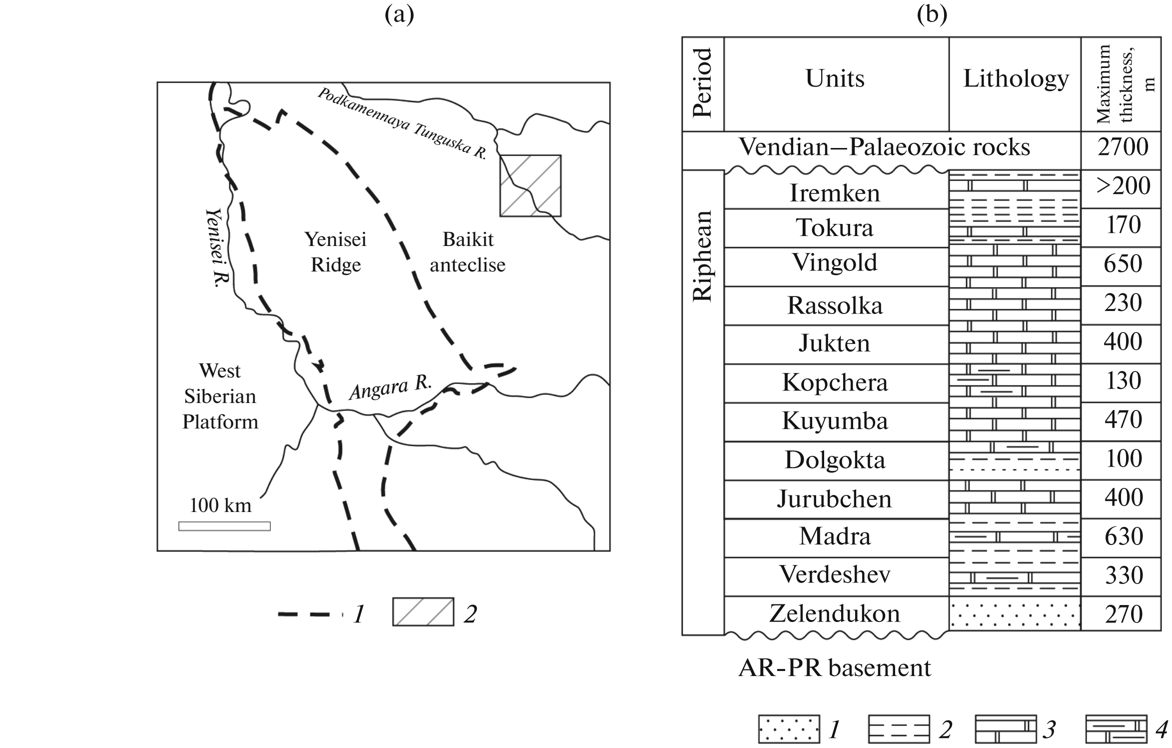

Fig. 1. (a) The schematic map of the study area: (*1*) boundaries of major tectonic structures, (*2*) study area. (b) The generalized stratigraphic column of the Riphean deposits of the Kuyumba group of deposits, after (Kharahinov and Shlenkin, 2011): (*1*) sandstone, (*2*) mudstone, (*3*) dolomite, (*4*) clayey dolomite.

sis of organic matter by Rock-Eval: this can be used with some reservations.

MATERIALS AND METHODS

Characterization of petroleogenetic rocks was carried by pyrolysis (Rock–Eval 6) on nine samples of mudstone from the Madra unit performed at the Geology and Geochemistry of Oil and Gas (MSU). The technique of the pyrolysis with Rock–Eval equipment has been developed at the French Institute of Oil and has been described in detail in a number of papers (e.g. Espitalie and Bordenave, 1993). Data published in the works of Filiptsov et al. (1999) and I.D. Timoshina (2005) provided additional material for the assessment of the subsidence and erosion.

The Results of the Study and Evaluation of the Subsidence and Erosion of the Riphean Rocks

The data (Table 1) showed that only two samples have pyrolyzable organic matter and the catagenesis grade was defined as the end of stage MK_3 to the beginning of stage MK_4, which corresponds to heating to 200–210°C (according to calculations (Ammosov et al., 1980)). The rocks for which it is impossible to determine T_{max} (in drill hole n1) have exhausted their petroleogenetic potential, i.e., they were transformed at a stage higher than MK_3. The content of organic carbon (C_{org}) is quite high for Riphean rocks and reaches 2.50 wt % with an average of 0.24 wt % in the Riphean clay rocks (*Spravochnik* ..., 1998; Neruchev and Rogozin, 2010). The measured values of total carbon content (TOC) are residual and well below the original due to the consumption of organic matter (OM) during the formation of hydrocarbons (HCs). The generation potential is almost entirely exhausted: S2 < 1 mg HC/g of rock. The hydrogen index values (HI < 100 mg HC/g TOC) are also residual. These parameters are in agreement and correspond to almost complete consumption of kerogen.

The summarized results of the degree of organic matter catagenesis in the Madra unit are shown in Table 2 and Fig. 2. The OM catagenesis degree is generally equal over the study area and ranges from MK_3 to MK_5.

It is known that each catagenesis degree corresponds to a certain temperature range (Ammosov et al., 1980), which, in turn, in the absence of additional heat sources (e.g., heating by intrusion of melt) determined by the depth of the rock occurrence. On the basis of the catagenesis degree of the samples, we calculated the paleodepth at which the rocks were buried. In this case, the studied samples were taken from wells with a known current depth of their occurrence. The catagenesis degree of the studied Riphean

Table 1. Rock-Eval results of rocks from two boreholes

Sample ID	Depth, m	Stratigraphic unit*	Lithology	S1, mg HC/g	S2, mg HC/g	S3, mg HC/g	TOC, wt %	T_{max}, °C	HI, mg HC/g TOC	OI, mg CO_2/g TOC	OM Catagenesis grade
n1	2307.5	dlg	Psammitic dolomite	0.1	0.29	0.31	0.37		78	84	
n1	2381.9	jrb	Secondary psammitic dolomite	0.28	0.59	0.28	1.44		41	19	
n1	2394.96	jrb	Same	0.38	0.64	0.2	1.38		46	14	
n1	2513.82	mdr	Mudstone	0.2	0.62	0.14	1.29		47	11	Higher than MK_{3-4}
n1	2514.44	mdr	Mudstone	0.16	0.49	0.17	2.26		21	7	Higher than MK_{3-4}
n1	2514.59	mdr	Mudstone	0.14	0.6	0.16	1.75		34	9	Higher than MK_{3-4}
n1	2515.02	mdr	Mudstone	0.17	0.7	0.14	2.23		31	6	Higher than MK_{3-4}
n1	2515.91	mdr	Mudstone	0.21	0.88	0.19	2.5		35	7	Higher than MK_{3-4}
n1	2527.31	mdr	Mudstone	0.18	0.51	0.27	0.93		54	29	Higher than MK_{3-4}
n2	3556.71	mdr	Mudstone	0.09	0.46	0.19	0.59	464	77	32	MK_{3-4}
n2	3556.77	mdr	Mudstone	0.12	0.68	0.12	1	462	67	11	MK_{3-4}

* Riphean units: dlg, Dolgokta; jrb, Jurubchen; mdr, Madra.

Table 2. Estimate of the palaeo-depth of the Madra unit occurrence and levels of erosion

No. of sample/ bore-hole	Present day depth of sampling, m	Sampling depth from the Vendian boundary, m	Catagenesis degree	Catagenesis temperature (after Ammosov), °C	Palaeo-depth, km	Corresponding erosion level, km
This study						
n1-28	2514	214	Higher than MK_{3-4}	>200	>7	>7 (?)
n1-30	2515	215	Higher than MK_{3-4}	>200	>7	>7 (?)
n1-33	2515	215	Higher than MK_{3-4}	>200	>7	>7 (?)
n1-34	2527	227	Higher than MK_{3-4}	>200	>7	>7 (?)
n2-51	3556	1142	MK_{3-4}	200–215	7	5.9
n2-52	3556	1142	MK_{3-4}	200–215	7	5.9
(Filiptsov et al., 1999)						
Mdr-156	3940–3948	1720	MK_4	210–220	7	5.8
Bds-1, Yur-30, Yur-45	2479–2487	200	MK_{4-5}	210–220	7	6.8
Yur-69	2681–2874	321–514	MK_{4-5}	210–220	7	6.5
(Timoshina, 2005)						
Mdr-156	3941–4003	1721	MK_5	210–220	7	5.3

deposits thus corresponds to a greater depth than the modern one: this allowed us to calculate how deep the explored deposits were. The value of the heat flow in the Riphean, according to experts (Watson, 1978; Beardsmore and Cull, 2001) is close to the modern level. The calculation results are shown in Table 2 and Fig. 2.

The calculations show that in order to achieve the value of catagenetic transformation of organic matter

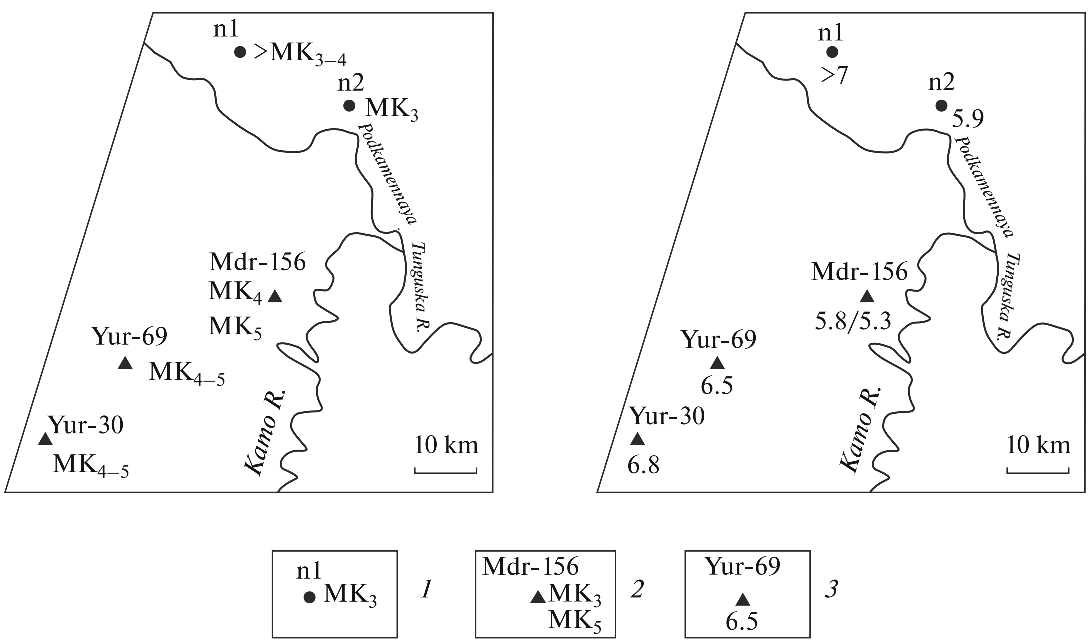

Fig. 2. Catagenesis grades for the Madra unit (left) and the level of erosion in some wells of the Kuyumba field (right): (*1*) drillhole number and catagenesis grade according to our results; (*2*) borehole number and catagenesis grade of according to (Filiptsov et al., 1999) and (Timoshina, 2005) (*italic*); (*3*) borehole number and evaluation of erosion level.

the Riphean rocks had to occur at a depth of approximately 7 km or more. To achieve levels of catagenesis the OM could undergo subsidence during the accumulation of the Riphean or Vendian–Paleozoic rocks. The Vendian–Paleozoic complex currently does not reach such a large thickness. Moreover, Filiptsov et al. (1999) noted catagenetic unconformity between the Riphean and Vendian–Paleozoic strata. However, the investigated samples occur at a depth of several hundred, or, rarely, 1000 m below the surface of the pre-Vendian unconformity and no more than 4 km from the original ground. This suggests that the Riphean rocks reached their catagenetic maturity before the beginning of the formation of the Vendian–Paleozoic cover.

Thus, it can be assumed that a substantial volume of the Riphean deposits were eroded in the pre-Vendian time; at the same time, the hydrocarbon generation potential of Madra Fm. mudstones is poor due to overmaturity. Our calculations have shown that the thickness of eroded rocks varies from 5.3 to 7.0 km in the study area (Fig. 2, Table 2). The youngest Riphean unit within study area is Iremeken Fm. However, it is not fully preserved in wells ascross Baikit anteclise. If we complete the sequence for each well for which the data are given in Table 2 by adding all of the known Riphean strata and evaluate the thickness of the complexes eroded above the Iremeken unit, which is the youngest unit that within the Baikit anteclise, this value will vary from 4 to 4.7 km for all the wells.

Therefore, the full realization of oil and gas potential of the Madra unit is connected to the fact that in the pre-Vendian time the Iremeken unit was overlain by a thick sedimentary sequence eroded later. There are several stratigraphic schemes, with different assessments of the age range of the Riphean complexes in the Baikit anteclise, for example (Kraevskii et al., 1997; *Stratigrafiya...*, 2005; Khabarov and Varaksina 2011). However, in recent years isotope and isotope–geochemical investigations indicated that the age of the entire Riphean sequence in the Baikit anteclise probably ranges from 1.5 to 1.1 Ga (Khabarov et al., 2002, Khabarov and Varaksina, 2011). At the same time, in a nearby Yenisei Ridge section of the lower Riphean deposits are overlain by a Middle–Upper Riphean unit that is some kilometers thick (Khabarov et al., 2002, Khabarov and Varaksina, 2011). The presented estimate of the catagenetic maturity degree of OM confirms idea (Khabarov and Varaksina 2011; Frolov et al., 2011) of a significant erosion of the Upper Riphean deposits within the Baikit anteclise.

CONCLUSIONS

Our results, along with the previously published data (Filiptsov et al., 1999; Timoshina, 2005; Frolov et al., 2011), have shown that the degree of catagenesis of the Madra unit OM within the Baikit anteclise is in general similar and ranges from MK_3 to MK_5. The oil-generation potential is almost entirely exhausted: S2 < 1 mg HC/g of rock. The hydrogen index values are also residual (HI < 100 mg HC/g TOC). Our calculations, based on the pyrolysis results of OM, showed that to achieve such a high catagenetic maturity the Madra unit rock had to be submerged to a depth of 7 km or more. The depth of the studied rocks is now less than 4 km. Considering the catagenetic disconformity between the Riphean and Vendian–Paleozoic complexes in the Baikit anteclise, we have shown that in the studied boreholes 5.3–7 km of the Riphean deposits have been eroded. Taking the thickness of the entire Riphean sequence in the Baikit anteclise and calculated thickness of eroded rocks into account, we assume that in the past the youngest Iremeken unit rocks were covered by Middle–Upper Riphean sediments 4.0–4.7 km thick: their stratigraphic equivalents now are known in the Yenisei Ridge. The cause and the intensity of the deformation that led to that voluminous erosion remain debatable.

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Translated by A. N. Larionov